CHAPTER 2

FACILITY ELEMENTS AND PROTECTION REQUIREMENTS

2-1. Generic C4ISR facility elements

To support its mission of gathering, processing, and transmitting information, the Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) facility contains as a minimum ten distinguishable elements. These are the structure or housing; electrical power generation and distribution [both alternating current (ac) and direct current (dc)]; non-electrical utilities; heating, ventilation, and air-conditioning (HVAC); an earth electrode; lightning protection; communications systems; computer and data processing systems; control and security systems; and personnel support systems.

a. Requirements. In general, C4ISR facility elements must conform to the requirements commonly encountered in commercial construction. However, because of their unique mission, the C4ISR facility elements must also accommodate several specialized requirements not found in commercial buildings or in military administration and support buildings. These specialized requirements impose restrictions on the configuration and installation of grounding networks and on bonding practices that are not common in routine construction. Fixed land-based C4ISR facilities range from small structures performing dedicated missions with few pieces of equipment to large complexes performing varied jobs involving many different kinds of signal and data processing equipment.

b. Facility characteristics. Regardless of the specific mission, land-based C4ISR facilities have certain characteristics that make them unique relative to administrative and support facilities. For example, in addition to commercial power, they commonly contain extensive on-site power generation capabilities for both emergency backup and power conditioning. Effective protection against electrical faults within this combined power system must be established. Also, because much of the information processed by the facilities is classified, TEMPEST measures must be taken to protect against unauthorized interception. In many locations, lightning presents a serious threat of damage to the sensitive equipment and protection must be provided. Hardness against disruption and damage from electromagnetic pulses (EMP) produced by nuclear blasts is also required in many facilities. Further, because of the amount of electronic data processing, transmission, and reception equipment in the facilities, there are many opportunities for electromagnetic interference (EMI) to occur. Integral to reliable operation of the C4ISR facility in this electromagnetic (EM) "environment" is the establishment of electrical fault protection networks and lightning discharge paths, the installation of interference control and surge suppression devices, and the implementation of EM shields between sensitive receptors and troublesome EM sources. Grounding and bonding are essential elements of these protective measures.

2-2. Element descriptions

Following are the descriptions of some common elements found in commercial and administrative facilities as well as in C4ISR facilities. For example, all facilities have structural, utility, HVAC, and personnel support elements. Other facilities may contain a number of the remaining elements.

a. Structure. The structure provides physical support, security, and weather protection for equipment and personnel. The structure is an element common to all facilities, yet it is the most varied. The size, configuration, material, and construction are rarely the same in any two C4ISR facilities.

(1) Wood, stone, glass, or concrete, which are essentially transparent to EM energy, provide little shielding to EMI and EMP threats.

(2) Structures containing steel reinforcing bars or steel superstructures offer some degree of EM protection. Other structures that have walls containing wire mesh, corrugated metal panels, aluminum siding, or solid metal foils or sheets offer still more protection against the transmission of EM energy into or out of the facility. Generally, as the metal content of the structure increases, so does the available EM protection. However, this protection depends heavily upon the electrical continuity (bonding) and topology of the structure. For example, structures which are completely enclosed by well-bonded steel sheets or plates with adequately treated apertures may provide over 100 decibels (dB) of protection from a few kilohertz to several gigahertz. On the other hand, open metallic construction may actually enhance coupling at frequencies where the members exhibit resonant lengths.

(3) Where TEMPEST or EMP protection is required, the structure of the C4ISR facility typically incorporates continuously bonded metal sheets in exterior walls or around rooms or clusters of rooms to provide a zonal barrier to prevent disruptive or compromising coupling of EM energy between internal equipment and the external environment. To maintain the shielding integrity of these EM barriers, all seams must be made electrically tight and all penetrations must be constructed and maintained to prevent unintended coupling of energy through the barrier. These penetrations include those required for personnel access, HVAC support, and signal and power transmission.

(4) For underground facilities, the housing typically consists of large interconnected metal rooms. The rock and earth overburden provides some degree of attenuation to EM energy; however, for complete EMP and TEMPEST protection, the added metal enclosures are necessary.

(5) The C4ISR facilities associated with the generation and transmission of high power radio frequency (RF) signals (e.g., long range radar installations or those providing high satellite linkages) commonly incorporate continuous RF shielding to control EMI to internal equipment. Similar requirements also exist in those facilities near commercial broadcast facilities or other RF-generating sources.

(6) Steel structural members offer many parallel conducting paths between various points within the facility and between these points and earth. These structural support members are frequently in direct contact with soil and can provide a low impedance path to earth. Because of the large cross-sectional areas of steel superstructural members, the net impedance between points is frequently less than that provided by lightning down conductors and electrical grounding conductors. For this reason, crossbonding between lightning down conductors and structural members is required to control flashover.

(7) Throughout the typical existing C4ISR facility, structural members are in frequent electrical contact with other facility elements either through intentional grounding or inadvertent grounding as a result of normal construction and installation practices. In general, structural members do not provide either adequate EM shielding or reliable power safety grounding. On the other hand, with proper bonding of structural members and with proper control of stray power return currents, the structure can be used to effectively augment grounding networks within the facility.

(8) The particular grounding and bonding requirements and constraints imposed on C4ISR structures are summarized in table 2-1.

b. Electric power generation and distribution. The power system is a network of electrical equipment, conductors, and distribution panels located throughout the C4ISR facility. The purposes of this network are to:

Table 2-1. Grounding and bonding principles for structures

Electrical Safety	Lightning	EMC	EMP	Signal Security
The structure cannot be substituted for the required equipment grounding conductor, i.e., "green wire." Wherever possible and convenient, the structure should be frequently interconnected with the fault protection subsystem. The structure should be frequently interconnected with the earth electrode subsystem.	All exterior metal walls must be bonded to lightning down conductors. No lightning protection subsystem conductors need penetrate the structural boundary of the facility. Bonds for the protection against lightning flashover must be connected to opposite sides of the structural boundary. Large exterior metal objects that are within 2 meters of down conductors must be cross-bonded to the nearest down conductor. Large interior metal objects and shielded rooms positioned within 2 meters of exterior steel structural members must be bonded to these members. Resistance of bonds should not exceed one milliohm.	To provide the lowest impedance facility ground system, all structural joints should be electrically well bonded.	All structural joints should be electrically well bonded. No untreated grounding conductors may penetrate or cross the structural boundary. External grounding conductors must be bonded to the outside of the structure. Internal grounding conductors must be bonded to the interior surface of the structure or enclosure.	No untreated grounding conductors may penetrate or cross the structural boundary. External grounding conductors must be bonded to the outside of the structure. Internal grounding conductors must be bonded to the interior surface of the structure or enclosure.

(1) Transform, as necessary, and route commercially supplied power into the facility.

(2) Generate appropriate on-line electrical power as required, especially during the absence of commercial power.

(3) Switch between these two sources of electrical power.

(4) Condition the electrical power for the critical loads being served.

(5) Provide uninterrupted electrical power for critical equipment in all situations.

(6) Distribute appropriate electrical power to the various equipment loads throughout the facility.

(7) The overall facility power system includes both ac and dc subsystems. A one-line diagram of a generic ac system is illustrated by figure 2-1. It consists of a substation/transformer bank, a number of

engine/generators (E/Gs), various switchgear, intermediate transformers, an uninterruptible power supply (UPS), transfer switches, and a network of conductors, disconnects, and distribution panels.

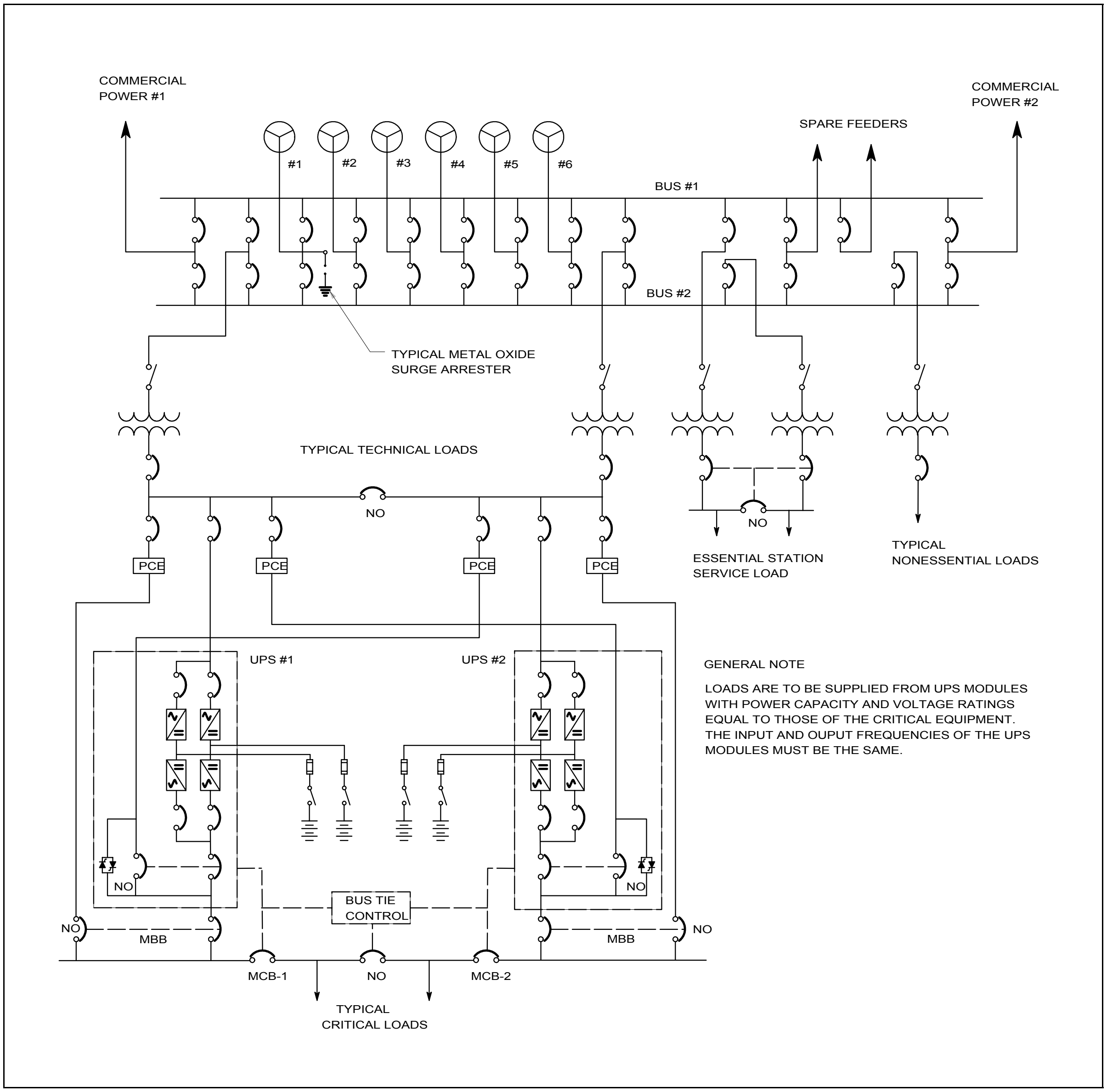

Figure 2-1. One-line diagram of a generic ac power subsystem

(8) The substation/transformer bank, which can range in size from a single pad-mounted transformer to a complete power substation, converts the incoming commercial power to the proper voltages for use at the facility. Commercial power is a primary ac power source for C4ISR installations wherever such sources are available and where operational and economic considerations permit. Independent, redundant sources are desirable. Thus, on-site electrical generators driven by diesel engines are commonly used to produce ac power as needed. The main facility switchgear is used to select one of the commercial power feeds or the generators as the primary source of facility power, to synchronize these sources, and to switch between them. In addition to having redundant feeds, this switchgear is configured with multiple buses so as to provide redundant paths to technical operational loads.

(9) C4ISR facilities contain four types of electrical/electronic equipment to which power must be supplied: critical technical, essential technical, non-essential loads, and emergency loads. Critical technical loads are those which must remain operational (100 percent continuity) in order for the facility to carry out its assigned mission. Essential technical loads are those which are supportive of the assigned mission but are not required to have 100 percent continuity. Non-essential loads indirectly support the C4ISR mission. Emergency loads consist of life-safety equipment such as emergency lights, exit lights, and fire alarm and suppression systems.

(10) The configuration of the ac power system following the main switchgear depends on the type of facility load being served. The critical and essential technical equipment loads are supplied through multiple bus switchgear and double feeds to provide redundant distribution paths. The non-essential loads are supplied through a single feed and single bus switchgear either from one bus in the main facility switchgear or directly from commercial power. In addition to the redundant distribution paths, the critical technical equipment loads are supplied through a UPS. The UPS provides continuous, high quality, uninterruptible power in all operational situations to the critical technical equipment within the facility. It consists of a rectifier bank driving a group of inverters, which generate the required ac power. Uninterruptible ac power results from paralleling the dc output of the rectifiers with a battery bank capable of carrying the critical facility load until the engine/generators are started, brought up to speed, and switched on-line. In addition, all incoming commercial and engine/generator power to critical loads is conditioned by the rectifier/battery/inverter process in normal operational situations.

(11) The output of the UPS is routed via multiple buses and redundant feeds through breakers in the critical bus switchgear to branch distribution panels. These branch panels are located throughout the facility at critical equipment locations. The critical power is then routed through circuit breakers in each of these panels to specific pieces of equipment.

(12) At appropriate locations in the power distribution paths, transformers and intermediate switchgear (indoor unit substations) and transfer switches may be employed. The transformers convert the ac power to the appropriate voltages and configuration (i.e., three-phase, delta or wye, or single-phase) for the loads being served. The transfer switches, which are typically automatic, switch between two sources of power to provide continuous operation in the event of failure of one of the sources.

(13) A typical configuration for the ac power system showing the neutral and grounding conductor is illustrated in figure 2-2. (To simplify this figure, the redundant buses in the switchgear and the redundant feeds are not shown.) Typically, every transformer between the ac power source and the load is a delta-primary/wye-secondary configuration, thus establishing a separately derived source at each transformer. Furthermore, the neutral is usually not run between intermediate switchgear. For example, although the neutral is usually present in the intermediate switchgear, it is usually not continued to the next successive transformer/switchgear assembly. It commonly begins at the last transformer prior to a single-phase load and is then routed with the phase conductors through the remaining switchgear and distribution panels to the loads.

(14) The dc power system usually consists of multiple battery racks located at various places in the facility and includes dc switchgear, battery chargers, and distribution conductors. In some C4ISR facilities, individual battery racks are located near the dc loads they serve; in others, a large battery rack called the station battery serves the function of, and replaces, several individual battery racks. The dc power system supplies appropriate power for switchgear circuit breaker controls, protective and auxiliary relays, and pilot lights; for other instrumentation and control signaling and switching; and for the UPS equipment. Since the major functions of the dc loads are associated with generation, monitoring, and control of the ac power, a significant portion of the dc power system is located near the ac power switchgear.

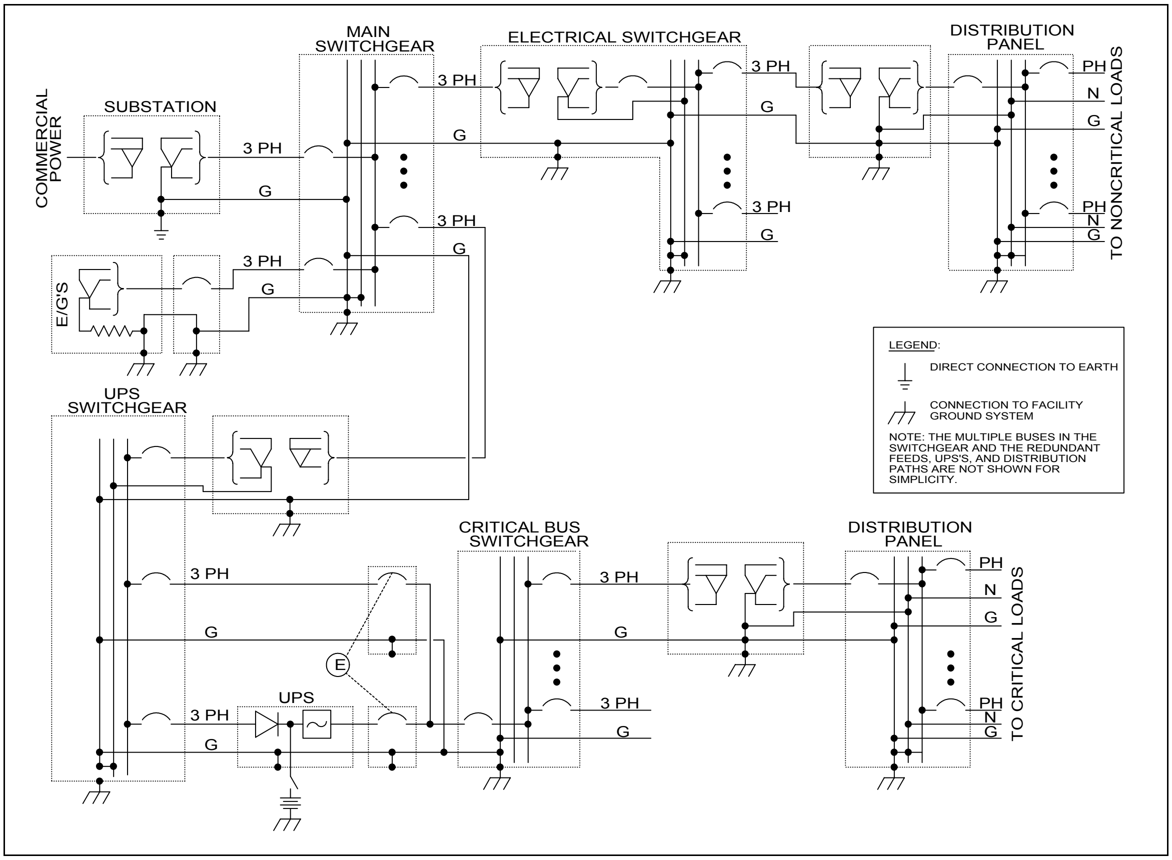

Figure 2-2. Typical ac power subsystem configuration

(15) In many facilities, there will be power conditioning centers dedicated to supplying highly filtered and protected power to data processing and other equipment demonstrated to be highly susceptible to power line transients and ground system noise. These centers commonly contain filters, terminal protection devices (TPDs), isolation transformers, voltage regulators, and overload protection. Depending upon the criticality of the equipment being served, a secondary UPS may also be provided by the power-conditioning center.

(16) The particular grounding and bonding requirements and constraints imposed on C4ISR electric power generation and distribution are summarized in table 2-2.

c. Non-electric utilities. Non-electric utilities are the non-electrical piping used for gas, sewer, and water (both for fire fighting and normal use). In addition to these normal services, the facility will likely contain other non-electric utilities such as fire suppression, chilled water, compressed air, etc. The utility pipes providing these services are typically constructed of steel, cast iron, copper, or plastic. Some buried sewer lines may be fired clay. In older facilities, the lines enter the facility at different points and then branch out to form an interwoven tree network of pipes. Metal pipes of different non-electric utility systems are frequently mechanically bonded together to become electrically continuous along their path. For example, gas and water pipes become interconnected at hot water heaters; water and sewer pipes interconnect at sinks and appliances; all may interconnect with structural elements via mounting brackets. Through chilled water and other coolant systems, the utility piping network can become electrically interconnected with electronic equipment. The internal piping is commonly joined electrically to the external system of pipes. This electrically joined network may provide coupling paths for unwanted

Table 2-2. Grounding and bonding principles for power distribution

Safety	Lightning	EMC	EMP	Signal Security
Ground the neutral of three-phase wye and single-phase supply lines at the service disconnect for the facility and/or individual buildings. Electrical supporting structures should be interconnected and connected with facility ground. Neutrals of engine generators should be grounded through a current limiting resistance or with a grounding transformer to the facility ground. The equipment grounding conductors, i.e., "green wire grounds," must be run with power conductors and connected to equipment frames and housings. Resistance of bonds should not exceed one milliohm.	Lightning ground must be interconnected with power ground. Surge suppressors installed on transformers shall be grounded to the transformer housings and their earth electrode connections with minimum length conductors Suppressors installed on service entrance panels shall be grounded to the common neutral-grounding conductor connection with minimum length connections. TPDs installed on power and control cables interfacing with HVAC elements must be grounded to the enclosure of the protected equipment with minimum length conductors. Resistance of bonds should not exceed one milliohm.	The neutral should not be grounded at any point on the load side of the disconnect, other than as required on the secondaries of delta-wye stepdown transformers or isolation transformers. (See exception for certain personnel support appliances. For this exception, however, it is essential that the frames or cabinets NOT be interconnected with the structure or fault protection subsystem.) All fuse and breaker panels, switch boxes, junction boxes, power outlets, electronic equipment enclosures, etc., MUST have no inadvertent neutral/grounding wire (white/green) reversal. All power conductors, including neutrals, entering or leaving protected regions should be equipped with EMI power line filters.	All power conductors entering or leaving protected regions of the facility must be equipped with EMP power line filters and TIDs. Grounding conductors must be bonded to the structure, EM shield, or EMP zonal boundary at the point of penetration of the power conductors. No untreated grounding conductors may penetrate or cross the structural boundary. External grounding conductors must be bonded to the outside of the structure. Internal grounding conductors must be bonded to the interior surface of the structure or enclosure. Multiple entry panels may be used; however, the aggregation of all penetrating conductors - power, signal, data, control lines, and utility conductors - to a single entrance panel or vault should be a goal during upgrades and continuing modifications of the facility.	All power conductors (including neutrals) entering or leaving Controlled Access Areas (CAA) must be equipped with EMI power line filters. Grounding conductors, i.e., green wires, must be bonded to outside and the inside surfaces of EM shields surrounding the CAA. A common grounding stud may be used to terminate the external and internal grounding conductors. External grounding conductors must terminate to the exterior part of shielded volume.

energy both between equipment internal to the facility and between internal equipment and the external environment, if adequate measures are not taken to disrupt the coupling path. The particular grounding and bonding requirements and constraints imposed on non-electric utilities are summarized in table 2-3.

d. Heating, ventilating and air conditioning (HVAC). HVAC is the network of equipment that regulates the internal physical environment of the facility. This system consists of the furnaces, air-conditioners, heat pumps, and humidifiers that condition the air, ducts, vents, and fans that distribute the conditioned air throughout the facility.

(1) The HVAC ducts are routed throughout the facility and are likely to make frequent contact with structural elements. The duct system may or may not be electrically continuous.

Table 2-3. Grounding and bonding principles for non-electrical utilities

Power Safety	Lightning	EMC	EMP	Signal Security
Except for gas lines, exterior pipes are to be bonded to the earth electrode subsystem and to the structure. Exterior gas supply lines shall be isolated from conductors inside the facility, if required by local codes. Metallic piping including gas lines inside the structure should be frequently interconnected with the facility ground.	Buried metal pipes must be bonded together and to the earth electrode subsystem.	All utility pipe penetrations into protected areas must be properly treated.	Utility pipes must be bonded to the structure at the point of penetration. If possible, peripheral bonding to a penetration panel or through a shielded entrance vault is preferred. All utility pipes should be bonded to the earth electrode subsystem at the point of crossing the subsystem. Utility pipes should have an insulating section inserted immediately outside the earth electrode subsystem. All utility pipes outside the zone oil boundary should be below grade.	All utility pipes entering CAA must be peripherally bonded to the CAA shield or utilize waveguide - below cutoff penetrations.

(2) Some components of the HVAC system, such as cooling towers and oil tanks, are usually outside the structure. These components can act as pickup conductors for lightning and EMP energy; thus, penetrating conductors such as fuel, water and coolant lines, and the protective conduit of electrical supply lines associated with external elements of the HVAC subsystem must be peripherally bonded. Electrical conductors must have appropriate transient suppressors and filters installed.

(3) The particular grounding and bonding requirements and constraints imposed onC4ISR HVAC systems are summarized in table 2-4.

e. Earth electrode. The earth electrode subsystem is a network of conductors buried in soil to establish an electrical connection between the facility and the body of the earth. This connection provides the primary path to ground for the facility and its contents:

(1) The network provides a preferential path to the earth for lightning discharge currents in a manner that protects the structure, its occupants, and the equipment inside.

(2) The network ensures that any faults in the facility substation or transformer-breaker system have a sufficiently low impedance return path between the fault and the generating source to reliably cause breakers (in the substation or in generators) to trip and clear the fault and to minimize voltage hazards until the fault is cleared.

(3) The network restricts the step-and-touch potential in areas accessible to personnel to levels below the lethal threshold even under lightning discharge and power fault conditions.

Table 2-4. Grounding and bonding principles for heating, ventilation, and air-conditioning

Power Safety	Lightning	EMC	EMP	Signal Security
Green wire grounds must be run with power conductors and connected to equipment frames and housings	Any external HVAC elements exposed to direct lightning strokes must have air terminals mounted thereon and be interconnected with roof and down conductors. Any other external HVAC equipment located within 2 m of roof and down conductors should be interconnected with the nearest down conductor. TPDs installed on power and control cables interfacing with HVAC elements must be grounded to the enclosure of the protected equipment with minimum length conductors.	Isolation Sections must be inserted in air ducts immediately prior to shield penetrations. Filters and TPDs installed for noise suppression and transient protection must be grounded to their mounting enclosures (which presumably is mounted directly on the housing of the HVAC equipment) with direct connections or with minimum length conductors.	Filters and TPDs installed for noise suppression and transient protection must be grounded to their mounting enclosures (which presumably is mounted directly on the housing of the HVAC equipment) with direct Connections or with minimum length conductors.	Isolation sections must be inserted in air ducts immediately prior to shield penetrations.

(4) The earth electrode subsystem commonly consists of both intentional and incidental metal conductors. Intentional conductors include ground rods (plus an interconnecting cable), grids, horizontal radials, or some combination of these. These conductors are generally placed around the perimeter of the structure, underneath the equipment as in the case of generators and high voltage transformers, or at penetration points of long external conductors. Since the C4ISR facility includes auxiliary generators and, typically, a commercial substation as integral elements of the power system, substation ground mats are likely to be a part of the facility earth electrode subsystem either through integral design or by extension through normal interconnections. Further, where auxiliary towers are a part of the complex, their grounds are also part of the earth electrode subsystem of the facility.

(5) Incidental earth electrode conductors are those buried objects that are directly or indirectly interconnected with the intentional earth electrode subsystem. Examples of incidental members of the earth electrode subsystem are underground storage tanks connecting to the facility via metal pipes, structural steel pilings, buried metal utility pipes (usually the cold water main), well casings, and, for underground facilities, conduit for power conductors and signal cables which penetrate the overburden.

(6) The particular grounding and bonding requirements and constraints imposed on the C4ISR earth electrode subsystem are summarized in table 2-5.

f. Lightning protection. A lightning protection subsystem is frequently installed to protect the structure, personnel, and equipment of the C4ISR facility from damage due to lightning discharges.

(1) The subsystem is a network of bonded air terminals and down conductors distributed over the exterior of the structure and connected to the earth electrode subsystem. The lightning protection subsystem also includes properly bonded support towers, to include their interconnections with the earth

Table 2-5. Grounding and bonding principles for earth electrode subsystem

Power Safety	Lightning	EMC	EMP	Signal Security
A low resistance connection to earth is required, i.e., 10 ohms or less. Ground mats or grids shall be installed as required to limit step-and-touch potentials in generating plants, substations, switching stations, and power conditioning centers. Except for gas lines, all nearby buried metal objects shall be interconnected to the earth electrode subsystem. Local codes may dictate that exterior gas supply lines be isolated from conductors inside the facility.	The earth electrode subsystem shall be configured as a ground rod and counterpoise ring around the facility. Ground connections must be 0.6 m outside the facility wall and must extend a minimum of 3 m into soil. Multiple paths between air terminals and the earth electrode subsystem must be installed. Except for gas lines, all nearby buried metal objects shall be interconnected to the earth electrode subsystem. Gas lines shall have a minimum 1 m insulating section installed outside at the point of penetration inside the facility and before crossing the earth electrode subsystem conductors.	No untreated conductors may penetrate protected areas.	All metal conductors shall be peripherally bonded to the earth electrode subsystem at the point of crossing or shall have insulating sections installed. No untreated conductors may penetrate protected areas.	No untreated conductors may penetrate protected areas.

electrode subsystem. Primary and secondary surge arresters on power lines, along with terminal protection devices on power and signal conductors located at penetration points into EM-protected areas, also are integral parts of the lightning protection subsystem.

(2) Air terminals are vertically mounted conductors placed on roof edges, ridges, corners, and any structural projection likely to receive a lightning stroke. Their purpose is to divert to themselves the lightning energy, which would otherwise enter the structure. Air terminals are interconnected with roof conductors routed along the roof edges and ridges.

(3) Lightning down conductors provide preferential paths for the lightning energy to follow from the air terminals and roof conductors to earth. Since analytical tools and measurement methods are not available for determining in advance the path of least resistance for a lightning discharge, down conductors are routed to follow the straightest and shortest path from the air terminals to earth. The down conductors must terminate to the lowest available impedance contact with earth, which should be the earth electrode subsystem for the facility.

(4) Lightning surge arresters are placed on the primary and secondary terminals of transformers supplying commercial power to the facility. These surge arresters are typically the robust spark gap variety used by the power utilities to protect against lightning strokes to the transmission network. Additional arresters are placed at penetration points into the facility and at subsequent step-down transformers, switchgear, the UPS, and other vulnerable equipment locations. These added arresters include both lightning surge suppressors and the fast-acting semi-conductor TPDs necessary for EMI and EMP transient suppression. Complete lightning and EMP protection also require that TPDs be placed on all exposed signal and control conductors at penetration points into EM-protected volumes.

(5) The particular grounding and bonding requirements and constraints imposed on the C4ISR lightning protection subsystem are summarized in Table 2-6.

Table 2-6. Grounding and bonding principles for lightning protection

Power Safety	Lightning	EMC	EMP	Signal Security
Any exterior metal objects within 2 m of lightning down conductors must be bonded to the down conductors. The lightning protection sub-system's earth connection must be common with the facility's earth electrode sub-system.	For above ground facilities, an air terminal, roof conductor, and down conductor net- work is required. At least two paths from each air terminal to earth must exist. Locate air terminals and down conductors so as to assure that all building extensions are effectively protected. Each down conductor shall terminate to a ground rod of the earth electrode subsystem. Lightning down conductors should be bonded to structural steel members at the top of the structure and near ground level. On towers, lightning down conductors should be periodically bonded to the tower structure along their downward paths. Resistance of bonds should not exceed one milliohm.	No untreated conductors may penetrate protected areas.	No untreated conductors may penetrate protected areas. No lightning protection subsystem conductors may penetrate the zonal boundary of the facility. Bonds for the protection against lightning flashover must be connected to opposite sides of the zonal boundary. The ground lugs of terminal protection devices shall be bonded to the distribution frame, junction box, penetration panel, or filter box where mounted. The frame, box, or panel must be grounded directly to the nearest point on the structure or on the EMP/EMI shield and, by extension, to the lightning down conductor and earth electrode subsystem.	No untreated conductors penetrate protected areas.

g. Communications systems. The communications subsystem is the network of electronic equipment, interfaces, and antennas whose elements are located both in, and around, the C4ISR facility. The purpose of the communications subsystem is to transfer information from one point to another. The information transfer may take place between points located within the facility or between different facilities.

(1) The electronic equipment making up the communications subsystem frequently include RF receivers and transmitters; audio, baseband, and RF amplifiers, data terminals and displays; telephones; modems; multiplexers; frequency converters; encryption devices; and other communication-electronic (C-E) equipment. Within the facility, the interfaces between equipment are generally hard-wired signal lines or waveguides. Signal penetrations into the facility include coaxial and waveguide for RF signals and, shielded, multiconductor cables for telephone, data, and control signals. Fiber optic penetrations are being increasingly used for EMP-protected facilities. Between facilities, the information transfer is usually via land lines or RF transmission. The RF antennas are generally located on or near the facility.

(2) The various communication sub-elements include telephone, radio, local area data transfer, and high-speed data. The telephone sub-element provides internal communications via hard-wired interfaces and intersite communications via land lines or microwave links. As a minimum, the telephone subsystem consists of the telephone instrument sets, cabling, and distribution frames. Larger facilities generally also have a private branch exchange (PBX), Centrex, and/or automatic switching racks, intercom apparatus, and a telephone power plant.

(3) The radio subsystem converts audio and baseband signals to a RF signal, radiates the RF signal to the receiving point, and then converts the RF signal back to the appropriate audio or baseband signal. Since it has both low frequency and RF equipment interconnected within the same network, the operating frequencies of the radio subsystem cover an extremely wide range.

(4) The low frequency signal interfaces to and from the RF equipment may be either single-ended or balanced, twisted-pair lines. Depending on the frequency of operation, the RF signal interfaces may be either coaxial lines or waveguides. These various types of interfaces are included within the radio subsystem.

(5) Another subsystem is equipment and cables associated with high-speed data transmission. This subsystem is used to transfer high-speed data signals between data processing equipment. The transmission paths employ both shielded twisted pair and coaxial cables.

(6) The equipment of the various communication elements is likely to be distributed throughout the facility and grounded at multiple points. The equipment cases, racks, and frames are grounded to the ac power ground, to raceways and conduit, and to structural members at numerous locations within the facility. In many facilities, a single point configuration for the signal reference ground is said to be implemented for telephone circuits and for data processing circuits. Actually, however, a single point ground configuration does not exist because of internal grounding of signal references to cabinets and enclosures with subsequent interconnections to power conduits and raceways and because of the use of unbalanced interfaces between the various pieces of equipment. Consequently, the effective signal reference ground for the communication subsystem in the typical C4ISR facility is a multi-point grounded system with numerous interconnections between signal references, equipment enclosures, raceways, conduit, and structural members.

(7) The particular grounding and bonding requirements and constraints imposed on C4ISR communications systems are summarized in table 2-7.

h. Computer and data processing systems. A distinguishing feature of the C4ISR facility is the presence of many digital processors ranging from microcomputers performing dedicated equipment and instrument control to large interconnected mainframes providing complex analyses, signal processing, and image displays. These processors typically interface with numerous input/output (I/O) devices including keyboards, monitors, disk drives, tape drives, remote terminals, data acquisition and control equipment, and other processors.

(1) The data processing subsystems are configured in various ways. These various configurations result in different grounding connections being established. For example, stand-alone desktop computers obtain power from single ac outlets and thus establish only one electrical safety ground connection. Other small computing systems may be configured so that the processor and I/O devices share the same outlet, or perhaps the same branch circuit. In this configuration, the ground connection is effectively a single connection although more than one physical tie is made. Where I/O and other peripherals are separated by large distances from the processor, multiple connections to the facility ground network result.

(2) Larger computing subsystems are generally characterized by having the processor in one place and the peripherals distributed throughout the facility. In this configuration, the peripherals are supplied from different ac outlets, off different branch circuits, or perhaps from different phases of the line. In

Table 2-7. Grounding and bonding principles for communications

Power Safety	Lightning	EMC	EMP	Signal Security
Green wire grounding conductor must be run with power conductors and connected to equipment cabinets.	The ground terminal of surge arresters and TPDs shall be bonded to the mounting enclosure with minimum length conductors. The enclosure shall be mounted directly to the tower structure or will be bonded with a minimum length, flat conductor.	A signal reference subsystem shall be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames, and racks; between conduit, raceway, and wireway; between these communication subsystem members and structures; and shall incorporate raised floors into the reference subsystem. Where space and accessibility exist, a wire mesh grid may be installed at floor level or overhead to supplement the above cabling network. Equipment enclosures and racks should be bonded to this wire mesh. The mesh should be bonded to structure at each point where structural members are accessible. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPDs installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPDs installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	A signal reference subsystem shall be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames, and racks; between conduit, raceway and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Where space and accessibility exist, a wire mesh grid may be installed at floor level or overhead to supplement the above cabling network. Equipment enclosures and racks should be bonded to this wire mesh. The mesh should be bonded to structure at each point where structural are accessible. Filters and TPDs installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPDs installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield shall be used.	A signal reference subsystem shall be established inside the Controlled Access Area (CAA). This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames and racks; between conduit, raceway and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Terminate shields of all cables in the CAA to the signal reference subsystem within the CAAs.

some installations, remote terminals may even be in separate buildings and supplied from different transformer banks. Each remote device must have a safety ground at its location. Noise in interconnecting paths can be encountered from stray currents in the ground reference network. The most practical approach to solving these noise problems is not to strive to implement a "single point" ground connection for the main processor but rather to minimize the stray current in the ground reference system and use effective common mode suppression techniques and devices in data paths.

(3) The particular grounding and bonding requirements and constraints imposed on C4ISR computer and data processing systems are summarized in table 2-8.

i. Control and security systems. Typical C4ISR facilities have many control and security devices which gather information and then automatically respond to a given situation by alerting personnel or engaging equipment to correct it. These subsystems range in nature from pneumatic and mechanical to electrical, electronic analog or digital, or a combination of these. Numerous current sensors, intrusion detectors, trip relays, sound detectors, remote control locks, remote control doors, and alarms are typically included in the systems.

(1) Many of the control subsystems are self-contained and independent, as, for example, intrusion detectors that sound alarms. Often, however, they interact with other facility elements. For example, the HVAC subsystem contains an integral network of temperature and humidity sensors along with actuators that control the interior air. For fire protection, smoke detectors, sound alarms, and temperature sensors start purging of the affected area. The power subsystem incorporates electronically operated circuit breakers to close or open circuits and to keep particular breaker combinations from being opened or closed simultaneously.

(2) Control subsystems range from being entirely automated to completely manual. One example of automated controls is that which switches over from commercial power to engine/generator power upon loss of commercial power. The control elements can automatically start the engine/generators, bring them up to proper speed and voltage, and switch the appropriate breakers. On the other hand, the operator has the option of performing each of these functions separately using selected devices of the control system to monitor the progress.

(3) In terms of grounding, the large diversity of the control subsystem results in various grounding paths being established. Small control devices are typically grounded through the ac safety ground provided via the power outlet. The more automated and complex subsystems, however, resemble a computer net or a communication subsystem. For example, sensors communicate information from their locations (which may be very remote) to a central location. In many cases, processors monitor the sensors, determine if an abnormal situation exists, and provide appropriate commands to control the necessary equipment. The processor may be the main facility computer. In such cases, the grounding network resembles that of both data processing and communications.

(4) Many control sensors and actuators are outside EM-protected portions of the facility. Particularly with automated control subsystems, these exposed portions are extremely susceptible to upset or damage from high level EM transients such as produced by lightning and EMP. Clearly, appropriate incorporation of shielding, terminal protection, grounding, and bonding are necessary. Specific attention must be paid to the filtering and terminal protection of control cables penetrating the boundary of the EM-protected volume, to effectively establishing adequate grounding paths for transient energy, and to accomplishing electrically tight bonds around the penetrations into control devices.

Table 2-8. Grounding and bonding principles for computers and data processing

Power Safety	Lightning	EMC	EMP	Signal Security
Green wire grounding conductor must be run with power conductors and connected to equipment cabinets.	The ground lugs of terminal protection devices shall be bonded to the distribution frame or junction box where mounted. The distribution frame or junction box must be grounded to the nearest structural frame member and, by extension, to the lightning down conductor. The shields of penetrating data lines shall be bonded to the entrance panel, or to the facility ground with a minimum length conductor. Data cable shields shall be bonded to antenna tower structural members at the point of departure from the tower.	A signal reference subsystem must be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames, and racks; between conduit, raceway, and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Where space and accessibility exist, a wire mesh grid may be installed at floor level or overhead to supplement the above cabling network. Equipment enclosures and racks should be bonded to this wire mesh. The mesh should be bonded to structure at each point where structural members are accessible. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPDs installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPDs installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	A signal reference subsystem must be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames, and racks; between conduit, raceway, and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Where space and accessibility exist, a wire mesh grid may be installed at floor level or overhead to supplement the above cabling network. Equipment enclosures and racks should be bonded to this wire mesh. The mesh should be bonded to structure at each point where structural members are accessible. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPDs installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPDs installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	A signal reference subsystem must be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames, and racks; between conduit, raceway, and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best.

(5) The particular grounding and bonding requirements and constraints imposed on C4ISR control and security systems are summarized in table 2-9.

j. Personnel support systems. Typically, C4ISR facilities are manned 24 hours per day. This means that in addition to routine office equipment, food, lodging, and recreational facilities are normally required for operating personnel on duty. This personnel support equipment includes those electrical devices that connect directly to the power system and do not interconnect with the communication, computer, or control system under normal operation. Devices such as office typewriters, lighting fixtures, kitchen equipment, cleaning apparatus, and electric tools are examples of personnel support equipment. Even non-electrical objects like carpeting, which can contribute to static charge build-up, need to be considered.

Table 2-9. Grounding and bonding principles for controls

Power Safety	Lightning	EMC	EMP	Signal Security
Green wire grounding conductor must be run with power conductors and connected to equipment cabinets.	The ground lugs of terminal protection devices shall be bonded to the distribution frame or junction box where mounted. The distribution frame or junction box must be grounded to the nearest structural frame member and, by extension, to the lightning down conductor. The shields of penetrating data lines shall be bonded to the entrance panel, or to the facility ground with a minimum length conductor. Control cable shields shall be bonded to antenna tower structural members at the point of departure from the tower.	Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPDs installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPDs installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPDs installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPDs installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	Control circuits penetrating the CCA must be treated as BLACK[1] conductors. They must be enclosed in continuous conduit, which are peripherally bonded at each end They must be powered from BLACK power. All penetrations through the CAA barrier must be thoroughly filtered. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPDs installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPDs installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.

[1] See paragraph 2-3a for definition of BLACK protection areas.

(1) Support equipment is usually electrically self-contained and has its own internal safety grounds. The connection to the power ground is via the three-pronged electrical plug, which connects to the "green" wire safety ground or otherwise provides an electrical safety grounding connection.

(2) Certain kinds of furniture and carpet may be responsible for the build-up of static charges. When personnel walking across carpet or in contact with furniture touch a piece of electronic equipment, a discharge can occur causing serious damage to solid-state devices. Computer and communication equipment is especially susceptible to damage of this type, particularly if they contain metal oxide semiconductor (MOS) integrated circuits. However, static build-up can be eliminated by proper choice of materials and by proper grounding of the offending objects and the affected equipment. Properly designed raised floors in data processing areas can largely fulfill this grounding requirement.

(3) The particular grounding and bonding requirements and constraints imposed on C4ISR personnel support systems are summarized in table 2-10.

Table 2-10. Grounding and bonding principles for personnel support equipment

Power Safety	Lightning	EMC	EMP	Signal Security
All exposed elements of electrical equipment and appliances should be grounded via the green wire ground to the fault protection subsystem, with the following exceptions: Certain types of high current, 220-volt appliances such as ranges, ovens, and dryers commonly are designed such that the neutral is grounded to the frame. These appliances shall not be grounded to the fault protection subsystem, to structure, nor to utility pipes. Doubly insulated, portable equipment does not need to be grounded, as per the National Electrical Code.			Waveguide-below-cutoff personnel entryways must be peripherally bonded to the supporting structure/shields.	

2-3. C4ISR facility protection requirements

The C4ISR facility requires different levels of protection dependent on the importance to national security for the area.

a. Protection areas. In the areas of protection two generic terms are used to depict the importance to national security. These terms are RED and BLACK. RED is applied to wire lines, components, equipment, and systems that handle national security signals, and to areas in which national security signals occur. BLACK is applied to wire lines, components, equipment, and systems that do not handle national security signals, and to areas in which no national security signals occur. The facility itself generally contains three areas requiring protection; these are the controlled access area (CAA), the Limited Exclusion Area (LEA), and the Controlled BLACK Equipment Area (CBEA).

(1) A controlled access area (CAA) is the complete building or facility area under direct physical control, which can include one or more LEA, CBEA, or any combination thereof.

(2) A limited exclusion area (LEA) is a room or enclosed area to which security controls have been applied to provide protection to a RED information processing systems' equipment and wire lines equivalent to that required for the information transmitted through the system. A LEA must include a RED equipment area.

(3) A controlled black equipment area (CBEA) is a BLACK equipment area that is not located in a LEA but is afforded the same physical entry control which would be required if it were within a LEA.

b. Practices. The grounding and bonding practices for the C4ISR facility must conform to the requirements for electrical safety and for lightning protection, must not compromise signal security, and must not degrade EMI control and EMP hardness. The ten identified elements of the generic C4ISR facility may therefore be logically divided into three categories.

(1) The first category includes those that must establish contact with earth in order to function correctly. In this category are the earth electrode subsystem and the lightning protection subsystem.

(2) The second category includes those elements which do not require grounding in order to perform their primary function, but which must be grounded for safety, for overvoltage protection, or because they tend to become part of the facility grounding system through convenience or accessibility. In this category are the structure, electrical power generation and distribution subsystem, utilities, HVAC, and personnel support.

(3) In the third category are those facility elements which must be grounded for fault protection and whose functioning may be severely impacted by improper grounding and bonding practices. This category includes the communications, data processing, and security and control systems. For these systems, in particular, the necessary protection against EMI, control of unwanted emissions, and EMP may be compromised unless proper grounding and bonding practices are followed.

c. Electrical safety (fault protection). The two primary goals of the fault protection subsystem are protection of personnel from exposure to electrical shock hazards in the event that short circuits or leakage paths occur between electrical conductors and exposed metal surfaces or objects and rapid clearance of fault conditions to minimize potential fire hazards. The electrical safety (fault protection) system falls in the second or third categories of protection.

(1) Effective electrical fault protection is achieved through the establishment of a low resistance contact with earth; the installation of ground mats or grids underneath high voltage transformers, circuit breakers and switchgear; and the installation of dedicated grounding conductors ("green wire") to equipment surfaces likely to become energized in the event of a fault.

(2) A low resistance connection to earth at substations and transformer locations simultaneously aids in clearing primary sideline faults while minimizing hazardous potentials. Since commercial power lines are highly exposed to lightning, the lightning surge arresters protecting the transformers, breakers, and switches are likely to be activated regularly. These lightning surge currents must be safely conducted to earth at the transformer/breaker location rather than through other, uncontrolled paths. This requirement can best be met with a low resistance, earth electrode subsystem at the power transformer/breaker/switchgear site.

(3) The purpose of the mats or grids under high voltage apparatus is to limit to safe values the step-and-touch voltages that are produced during high current fault conditions and during lightning surge arrester firings. In this way, if a fault occurs while personnel are in the substation or switchgear room, the voltages to which they are exposed remain within non-lethal ranges. Mats and grids are also effective in establishing a low resistance contact with earth. This low resistance is helpful in minimizing the voltage differential between objects in contact with the mat and personnel or objects not in contact with the mat.

(4) As a further protective measure against hazardous step-and-touch potentials during faults and lightning discharges, all metal objects, such as gates, fences, towers and barriers, which are in the immediate vicinity of the transformer/breaker site must be electrically interconnected with the grounding system for the site.

(5) A dedicated fault current return path must be installed between all potential fault locations and the source at E/Gs, transformer secondaries, and service disconnects. Thus all electrically powered equipment and the conduit, raceway, breaker panels, and junction boxes associated with the electrical distribution system must be electrically interconnected with the "green wire," or the "equipment grounding conductor" specified by the *National Electrical Code®*. This equipment grounding conductor is connected to the source neutral at all engine/generators, transformer secondaries and service entrance disconnects. (Reprinted with permission from NFPA 70-2002, the *National Electrical Code®* Copyright© 2002, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the referenced subject which is represented only by the standard in its entirety.)

(6) In order to prevent ac return current from flowing in the power grounding network, the neutral must not be grounded at any point following the first disconnecting means of a separately derived system or the building (i.e., "main") disconnecting means of an ac supply originating outside the building served.

(7) The generators, transformers, power converters, and power conditioners within the C4ISR facilities constitute "separately derived systems." Figure 2-3 shows the required grounding for separately derived systems.

(a) Article 250-20(d) of the *National Electrical Code®* defines separately derived systems as "a premise wiring system whose power is derived from generator, transformer, or converter windings and has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system." An alternate power source cannot be considered as a separately derived system if its neutral is solidly interconnected to a normal utility service supplied system neutral. Figure 2-4 shows the required grounding for non-separately derived systems.

(b) Separately derived systems are grounded for fault protection and personnel safety in the same way as normal ac supply systems. The neutrals from the wye windings of generators and the wye secondaries of transformers are bonded to the fault protection subsystem. Article 250-28 of the *National Electrical Code®* specifies that a bonding jumper sized in accordance with table 250-66 be used to interconnect the equipment grounding conductors of the separately derived system to the grounded conductor of the separately derived system. Further, this connection may be made at any point between the source and the first disconnecting means for that separately derived source. Confusion can arise between "the first disconnecting means for a separately derived system" and "the building disconnecting means" for normal commercial service.

(c) The intent for either separately derived sources or normal commercial ac service is to have the grounded conductor (as defined in Article 250-24) made common with the grounding conductor so as to complete the fault return path and to prevent the grounded conductor from contacting the grounding conductor at any point beyond the service disconnect for that particular ac service. Thus, the interconnection of the neutrals of transformer or generator wye windings to building steel and the

interconnection of the neutral conductor to the grounding conductor at the first disconnect following the transformer or generator fulfills the requirements of the Code. This requirement for the interconnection of neutral to the grounding conductor applies to both normal ac service and separately derived systems. The neutral is not grounded for non-separated derived systems, which have a bonded neutral conductor, to avoid incorrect operation of overcurrent devices during ground faults. Beyond this disconnect, no connections may be made between the grounded conductor (the neutral) and the safety grounding conductor.

(d) Except where single-phase loads are involved, the neutrals are not continued beyond the disconnect of separately derived systems or the disconnect for the building, as appropriate. Where single-phase loads are served, both the neutral and the grounding conductor are continued to the loads. The grounding conductor must be run with the phase conductors, which include the neutral.

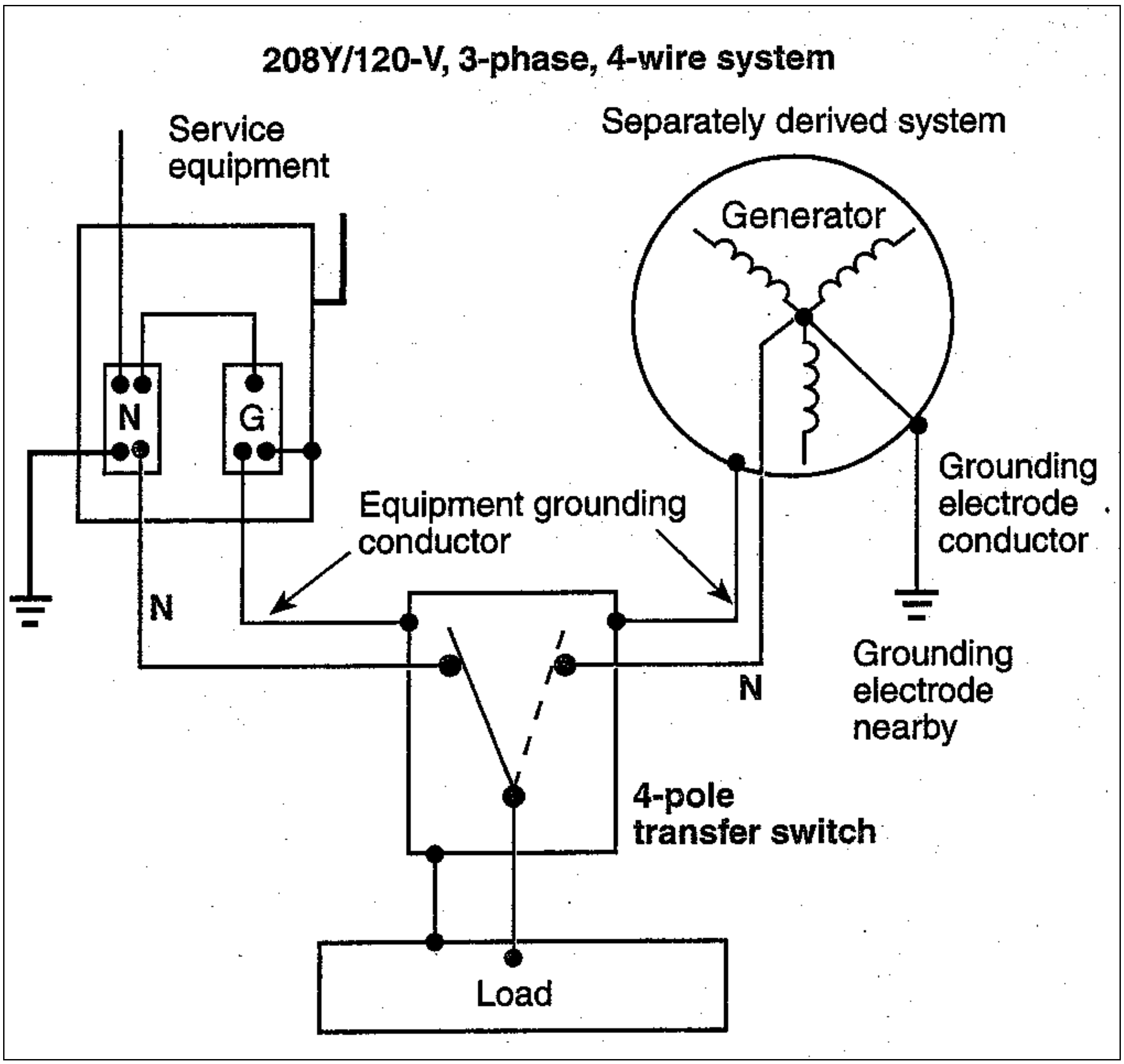

Figure 2-3. Required grounding for separately derived systems

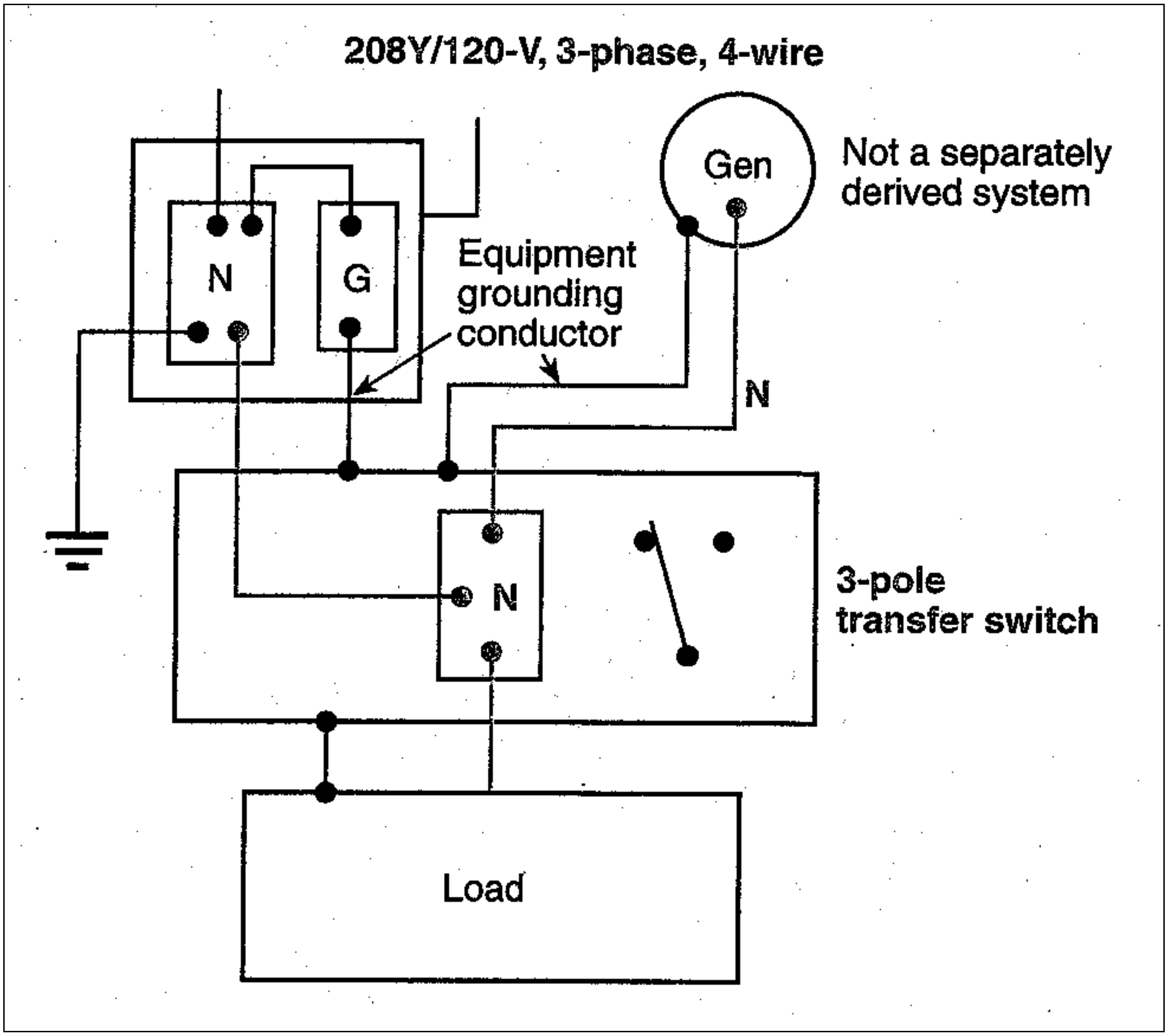

Figure 2-4. Required grounding for non-separately derived systems

(e) A major category of equipment that is exempted from this prohibition of grounding of the neutral includes ranges and clothes dryers. These personnel support equipment typically have their neutrals connected to the frames. Consequently, these appliances should not have their frames interconnected with the remaining elements of the facility grounding system, including utility pipes.

(8) At engine/generator locations, low resistance contacts with earth are typically installed. In indoor locations where operating personnel may be reasonably isolated from intimate contact with earth, the necessary fault protection reference for multiple engine/generators can be achieved through the installation of a copper bus bar of adequate cross section around or throughout the engine/generator area. This bus in turn is connected to the fault protection subsystem or to the earth electrode subsystem at the

motor/generator if the engine/generator is a separately derived system, i.e. its neutral is not solidly connected to the neutral of the normal ac supply. If the engine/generator neutral were solidly tied to the normal ac supply the engine/generator would not be considered a separately derived system and the generator neutral would not be grounded. A four-pole transfer switch, which transfers the neutral conductor or a transfer switch with overlapping neutral make-before-break contacts, is normally used for transferring between separately derived power sources, i.e. the normal ac supply and the engine/generators instead of a three-pole transfer switch. For additional reference material on grounding of engine/generators see IEEE 446-1995, Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications.

(a) Where phase-to-neutral loads must be served, engine/generators are required to be solidly grounded. However, 600 volt and 480 volt systems may be high resistance grounded or ungrounded where a grounded circuit conductor is not used to supply phase-to-neutral loads.

(b) High resistance grounded or ungrounded engine/generators may provide a higher degree of service continuity than solidly grounded engine/generators. High resistance grounding combines some of the advantages of solidly grounded systems and ungrounded systems. System overvoltages are held to acceptable levels during ground faults, and the potentially destructive effects of high magnitude ground currents are eliminated. With high resistance grounding, ground fault currents are normally limited to 10 amperes or less to allow continued operation of a system until the fault is located and cleared. However, if a ground fault is not located and cleared before another ground fault occurs, the high magnitude ground currents will flow through the equipment grounding conductors and operate the circuit protective devices.

(c) Where phase-to-neutral loads are not served, low resistance grounding of engine/generators may be used where limiting the ground-fault current is important. Such grounding may be used to limit damage to large engine/generators. There is also an additional element of protection for personnel who may be working on or near the engine/generator. The size of the resistor can be set to limit the current to 100 amperes; however, the 200-1000 ampere range is more typical. This provides sufficient current to operate the motor protective devices for a line-to-ground fault. The neutrals of the engine/generators are typically connected to ground through low resistance grounding resistors.

d. Lightning protection. The lightning protection requirements seek to protect personnel, buildings, and equipment from the high voltage and current transients produced by lightning discharges. A major element of this protection is achieved by providing a means by which a lightning stroke can bypass the facility and enter the earth without causing damage. The stroke current must first be intercepted before it penetrates the structure. Air terminals are provided for this purpose. Preferential paths must then be offered which the stroke current will follow instead of any others. To provide these preferred paths, down conductors are designed to have large diameters and are routed to be as straight and short as possible. Finally, a low impulse impedance connection with the earth must be made.

(1) "Side flashes" between the down conductors and internal conducting objects within the facility can occur because of the inherent inductance of the down conducting path. The internal conducting objects must be interconnected with the down conductors to prevent this flashover. However, EMP and TEMPEST protection practices prohibit unprotected conductors from penetrating the EM boundary, which in many facilities is the exterior wall of the structure. Fortunately, the connection for preventing flashover can be made without violating the EMP restrictions by bonding the cross conductors to the outside and the inside, respectively, of the exterior wall (with no direct penetration).

(2) An essential addition to the air terminals, down conductors, and earth connection for the protection of electrical and electronic equipment is the installation of lightning arresters and terminal protection devices (TPDs) on all external power, communications, data, and control lines that penetrate the facility boundary. TPDs are fast-response protection devices installed for the purpose of shunting

extraneous pulses to ground. Examples of commonly used terminal protection devices are carbon blocks, gas-filled spark gaps, zener diodes, and EMI power and signal line filters. These devices must respond in a sufficiently short time to limit the surge voltages produced by the lightning discharge to levels, which can be tolerated by the equipment inside the facility. To obtain least response time and to limit the overshoot voltage of the arresters and TPDs, these devices must be properly grounded. They must be installed such that their leads are kept to minimum lengths and kept very near to facility ground conductors.

e. Electromagnetic (EM) interference. Each of the electronic subsystems found in C4ISR facilities contain several pieces of equipment that must work together as an integrated unit. Communication and data transfer between the equipment consists of analog, digital, RF, or audio signals. Extraneous energy from other equipment within the facility or from sources outside the facility can degrade performance or damage components.

(1) To prevent such interference or damage from occurring it is necessary that the level of the interfering signal at the susceptible component be reduced by relocating the sensitive equipment inside a shielded volume and by shielding and filtering the power and signal conductors. Grounding, in and of itself, is not part of the interference control process. Yet the method of grounding filters and equipment cases and the bonding of cable shields can influence the performance of shields and filters and other EMI protective measures.

(2) Grounding is required for lightning protection and for electrical safety. In most installations, signal references will not remain isolated from the safety and lightning protection grounds. For example, signal paths between equipment often use unbalanced transmission lines in which the low, signal return side is electrically interconnected with the case. Since the case must be grounded for electrical safety, the signal reference ground and the power safety become common. This interconnection between the signal reference and the power safety ground gives rise to the frequently mentioned "ground loops." The stray current flowing in the common "ground" produces the common-mode voltage between interconnected equipment. Such voltages can produce a differential noise voltage in the terminating loads of the equipment, which can disrupt the intended operation of the system or damage circuit components. The degree of interference or upset experienced in a given situation is dependent upon the impedance of the common path, the amplitude of the stray current in the path, the common-mode rejection of the cabling between the equipment and the internal circuitry of the equipment, and the relative susceptibility of the circuits to the coupled noise currents. Typically, the most serious contributors to "ground loop interference" are the very high stray power currents present in the fault protection subsystem of C4ISR facilities. These currents commonly arise from electrical wiring errors, which interchange the neutral (white) and grounding (green) conductors. Other contributors to troublesome grounding network noise currents are filter capacitors in shunt across power lines and improperly wired electronic equipment. Particular attention needs to be paid to locating and correcting excessive stray power currents wherever they exist.

(3) A frequently encountered recommendation for eliminating "ground loop noise" in signal and data circuits is to install a single point ground. The single point ground seeks to isolate the entire signal processing circuitry in the interconnected equipment from the fault protection subsystem except for one connection. To achieve a truly single point grounded complex of equipment requires extraordinary attention to assuring that all pieces of equipment except one are completely isolated from the fault protection subsystem. Not only must the complex be laid out to be fed from a single ac power source, but also no hardwired signal, control, or other type of lines may interconnect with other equipment outside the complex. Not only are these constraints difficult to achieve at initial installation but they are also impractical to maintain over any extended period of use. Consequently, single point grounded systems are being replaced with multiple point grounded systems. A multiple point grounding system is a grounding system with multiple connections to earth. In addition, as noted in the previous section, even

in those locations where single point ground networks are said to be installed, normal installation practices typically produce a multiple point, interconnected grounding system.

(4) The merits of the multiple point ground are that it is straightforward to install since it does not demand special training or procedures, and it is simple to maintain during normal operation and through successive upgrades or retrofits.

f. Electromagnetic pulse (EMP). The EMP generated by a nuclear explosion presents a harsh EM environmental threat with lightning being the closest comparable threat. Exo-atmospheric nuclear bursts can develop pulses of EM energy whose amplitudes can approach 50,000 volts/meter over geographical regions nearly the size of the continental United States. Such high amplitude, short duration EM fields can induce currents into long unprotected conductors sufficient to cause operational upset and component burnout in C4ISR equipment.

(1) Since the EMP threat is significantly different from any other man-made or natural EM threat, the measures that are routinely incorporated for protection from non-EMP environments are not adequate. For example, the structures that are intended to house equipment in non-EMP environments are typically not designed nor constructed with an aim toward providing the extensive EM shielding needed for EMP protection.

(2) Effective EMP protection requires the construction of a closed EM barrier surrounding the susceptible equipment. The realization of an EM barrier involves the construction of an effective shield, the treatment of shield penetrations and apertures, and correct grounding and bonding.

(a) Shielding involves the use of metallic barriers to prevent the direct radiation of incident energy into the system and internal enclosures and to minimize the coupling of energy to cables and other collectors which may penetrate these barriers. Shielding is the basic element of any barrier design, and little EMP protection is possible without its proper use. A completely solid shield is not possible since mechanical and electrical penetrations and apertures are necessary. These openings must be properly treated, or "closed," to prevent unacceptable degradation in the effectiveness of the shield. Grounding and bonding, by themselves, do not directly provide protection against EMP. However, they form an integral part of, and are inseparable from, enclosure shield designs and penetration and aperture treatments. Proper grounding and bonding techniques and practices must be followed if violations in the integrity of EMP shields and of penetration and aperture treatments are to be avoided.

(b) In some existing C4ISR facilities, it may be possible to enclose the entire building containing critical equipment, including power, inside a well-bonded metal shell. In most situations, however, surrounding the total building with a metal shell will be extremely difficult and extraordinarily expensive. For the majority of cases, shielding of only part of the volume of the building will be realistic. In perhaps a small number of facilities, the necessary amount of EMP protection can be achieved by only shielding individual equipment enclosures.

(c) Inside a volume, shielded with solid metal, the primary purpose of grounding is to achieve electrical safety. A facility not totally shielded may be conveniently divided into EM zones. Outside the structural walls of the facility is defined as Zone 0. Inside the facility outer walls, but outside equipment enclosures or internal shielded rooms, is then Zone 1. Thus, the facility outer structural walls become the Zone 0/1 boundary. (For underground facilities, the rock-earth overburden may be considered to be the Zone 0/1 boundary.) Zone 2 is then inside the electronic enclosure or inside the shielded room, if present. Higher ordered zones may also be defined, according to the level of compartmentalization employed.

(d) In the absence of a solid metal, well-bonded shield for the Zone 0/1 boundary, certain steps can be taken to minimize the coupling of EMP energy into the facility. Minimal steps include

implementing low resistance bonds across structural joints and assuring that utility pipes are effectively bonded to the earth electrode subsystem where they cross, or to the facility ground subsystem at the point where the pipes enter the facility. Fast acting surge suppressors should be installed across entering power and signal lines.

(e) More substantial steps include augmenting the shielding properties of the structure by installing wire mesh or sheet metal. The added metal must be continuously joined at the seams and joined to the existing structural steel members with soldered or welded connections.

(f) More comprehensive EMP treatment involves rerouting utility, electrical, and signal conductors into the facility through a well-shielded entry vault or through an entry plate positioned at or below grade level with a short interconnection with the earth electrode subsystem. Surge arresters and TPDs should be returned to the entry vault walls or to the entry plate with minimum length conductors.

g. Signal security. Equipment that processes classified information may produce signals capable of unauthorized detection. To prevent such security compromises, measures must be taken to reduce sensitive data signals to levels low enough to make detection impossible in areas accessible to unauthorized personnel. These measures include controlled grounding practices.

(1) The recommended approach to TEMPEST grounding is illustrated in figure 2-5. All equipment cabinet grounds, RED signal grounds, and BLACK signal grounds are made to the ground reference established inside the CAA. Both RED and BLACK cable shields are peripherally bonded to equipment cabinets at both ends. The low sides of BLACK data lines are connected to cable shields in the BLACK intermediate distribution frame (IDF) and both are grounded to the ground reference plane. Notice that BLACK cables should exit the controlled area via filtered couplings through the CAA boundary.

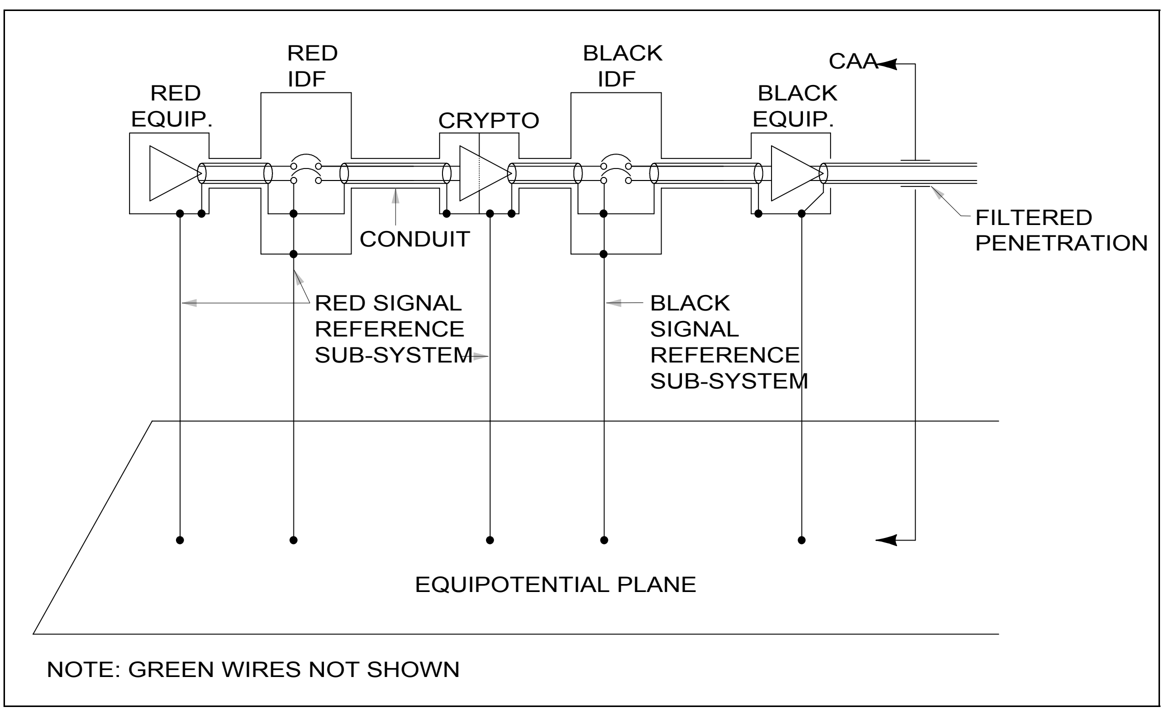

Figure 2-5. Recommended TEMPEST signal reference subsystem

(2) Figure 2-6 depicts the grounding approach recommended for ac power distribution in secure facilities. Note that both the neutral and phase conductors are filtered. As discussed earlier, the neutral is grounded only at the service disconnect. The cases of all subsequent distribution panels, filter enclosures, technical power panels, and equipment are all interconnected with the deliberately installed grounding conductor. Note that the equipment cases are connected to the BLACK signal reference system, which is grounded to the reference plane.

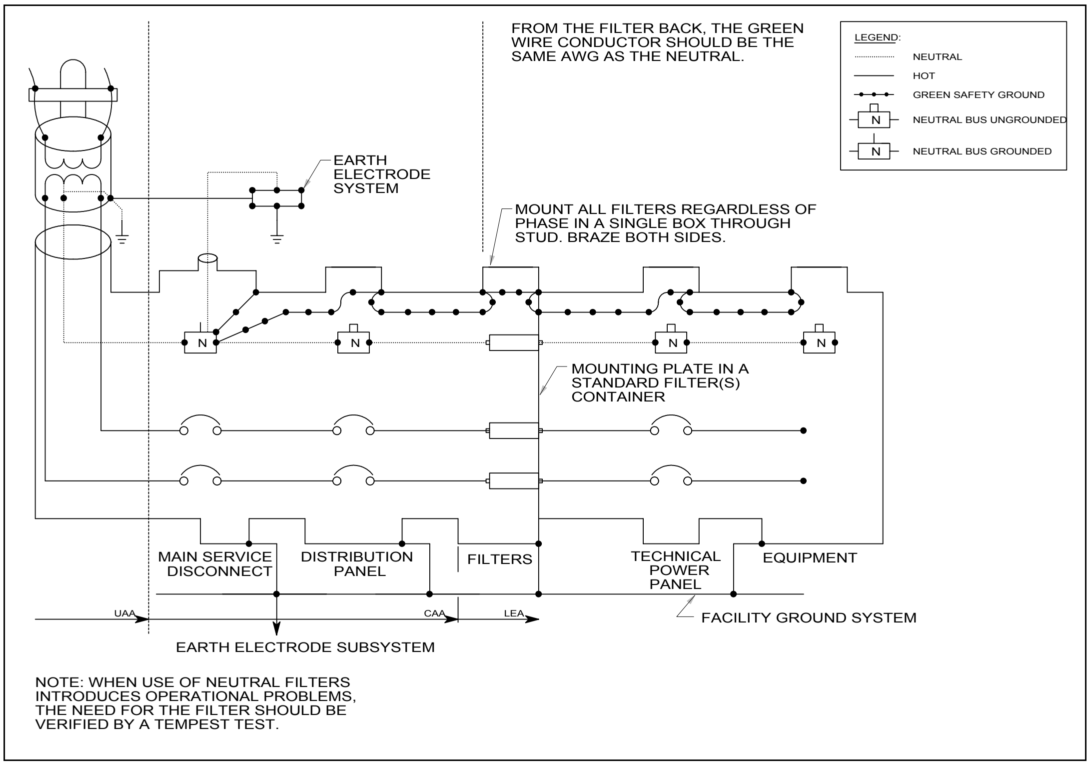

Figure 2-6. Recommended power grounding for secure facilities

2-4. Role of grounding

The C4ISR grounding system consists of four subsystems, (1) the earth electrode subsystem, (2) the fault protection subsystem, (3) the lightning protection subsystem, and (4) the signal reference subsystem. The purpose of the earth electrode subsystem is to provide a path to earth for the discharge of lightning strokes, prevent shock hazard to personnel, and assist in the control of noise. The primary purpose of the fault protection subsystem is the protection of circuits and equipment by ensuring prompt operation of overcurrent devices and protection of personnel from electric shock hazards. The primary purpose of the lightning protection subsystem is the reduction of overvoltages due to lightning and power system surges. The primary purpose of the signal reference subsystem is the reduction of EMI due to EM field, common ground impedance, or other forms of interference coupling. The various grounding systems used are integral parts of a facility or system.

a. Facility ground network design. The facility ground network design should consider all aspects to the degree required for the particular mission of the facility in its environment and in the context of costeffectiveness. The use of the term facility ground network is intended to be in the collective sense; it includes the power fault protection network, lightning protection network, building or structure ground, equipment ground, signal ground, instrument ground, data ground, etc.

b. Installation requirements. Requirements for the safe installation of electric conductors and equipment within or on various facilities are contained in the *National Electrical Code*® NFPA 70-2002.

c. Separation of equipment grounding. The grounding of the electrical system and connection of the electrical system neutral to earth must be separated from the equipment grounding. Reasons for the electrical system to be grounded are stabilization of the voltage (that is, to keep it from floating above a set reference point), facilitation of clearing phase to enclosures/ground faults, and limitation of lightning and line surges.

2-5. Role of bonding

Bonding refers to the process by which a low impedance path for the flow of an electric current is established between two metallic objects. In any realistic electronic system, whether it be only one piece of equipment or an entire facility, numerous interconnections between metallic objects must be made in order to minimize electric shock hazards, provide lightning protection, establish references for electronic signals, etc. Ideally, each of these interconnections should be made so that the mechanical and electrical properties of the path are determined by the connected members and not by the interconnection junction. Further, the joint must maintain its properties over an extended period of time in order to prevent progressive degradation of the degree of performance initially established by the interconnection. Bonding is concerned with those techniques and procedures necessary to achieve a mechanically strong, low impedance interconnection between metal objects and to prevent the path thus established from subsequent deterioration through corrosion or mechanical looseness.

a. Bonding objectives. In terms of the results to be achieved, bonding is necessary for the:

(1) Protection of equipment and personnel from the hazards of lightning discharges;

(2) Establishment of fault current return paths;

(3) Establishment of homogeneous and stable paths for signal currents;

(4) Minimization of RF potentials on enclosures and housings;

(5) Protection of personnel from shock hazards arising from accidental power ground; and

(6) Prevention of static charge accumulation.

b. Effects of poor bonds. With proper design and implementation, bonds minimize differences in potential between points within the fault protection, signal reference, shielding, and lightning protection networks of an electronic system. Poor bonds, however, lead to a variety of hazardous and interference-producing situations.

(1) For example, loose connections in ac power lines can produce unacceptable voltage drops at the load, and the heat generated by the load current through the increased resistance of the poor joint can be sufficient to damage the insulation of the wires which may produce a power line fault or develop a fire hazard or both. Loose or high impedance joints in signal lines are particularly annoying because of intermittent signal behavior such as decreases in signal amplitude, increases in noise level, or both. Poor joints in lightning protection networks can be particularly dangerous. The high current of a lightning discharge may generate several thousand volts across a poor joint.

(2) Degradation in system performance from high noise levels is frequently traceable to poorly bonded joints in circuit returns and signal referencing networks. As noted previously, the reference network provides low impedance paths for potentially incompatible signals. Poor connections between elements of the reference network increase the resistance of the current paths. The voltages developed by the currents flowing through these resistances prevent circuit and equipment signal references from being at the same reference potential.

(3) Poor bonds in the presence of high-level RF fields, such as those in the immediate vicinity of high powered transmitters, can produce a particularly troublesome type of interference. Poorly bonded joints have been shown to generate cross modulation and other mix products when irradiated by two or more high level signals. Some metal oxides are semiconductors and behave as nonlinear devices to provide the mixing action between the incident signals. Interference thus generated can couple into nearby susceptible equipment.

c. Importance of Bonding. Bonding is also important to the performance of other interference control measures. For example, adequate bonding of connector shells to equipment enclosures is essential to the maintenance of the integrity of cable shields and to the retention of the low loss transmission properties of the cables. The careful bonding of seams and joints in EM shields is essential to the achievement of a high degree of shielding effectiveness. Interference reduction components and devices also must be well bonded for optimum performance.

2-6. Role of shielding

Shielding involves the use of metallic barriers to prevent the direct radiation of incident energy into the system and internal enclosures and to minimize the coupling of energy to cables and other collectors that may penetrate these barriers. Shielding is the basic element of any barrier design, and little EMP protection is possible without its proper use. A completely solid shield is not possible since mechanical and electrical penetrations and apertures are necessary. These openings must be properly treated, or "closed," to prevent unacceptable degradation in the effectiveness of the shield. Grounding and bonding, by themselves, do not directly provide protection against EMP. However, they form an integral part of, and are inseparable from, enclosure shield designs and penetration and aperture treatments. Proper grounding and bonding techniques and practices must be followed if violations in the integrity of EMP shields and of penetration and aperture treatments are to be avoided.